La Palma night-sky brightness

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Abstract

The brightness of the moonless night sky above La Palma was measured on 427 CCD images taken with the Isaac Newton and Jacobus Kapteyn Telescopes on 63 nights during 1987 - 1996. The median sky brightness, in units of mag arcsec^{-2}, at high elevation, high galactic latitude and high ecliptic latitude, at sunspot minimum, is B = 22.7, V = 21.9, R = 21.0, similar to that at other dark sites. The sky brightness in U and I is less well-determined, U $\approx$ 22.0 (few data), I $\approx$ 20.0 mag arcsec^{-2} (variable). As at other dark sites, the main contributions to sky brightness are airglow and zodiacal light, in the ratio 2.5:1 at high ecliptic latitude.

- The sky is brighter at low ecliptic latitude (by 0.4 mag); at solar maximum (by 0.4 mag); and at high airmass (0.25 mag brighter at airmass 1.5).
- The mean brightness of the sky varies by < 0.1 mag with time after astronomical twilight.
- Light pollution is visible to the naked eye at certain azimuths on the horizon, but its contribution to the continuum brightness at the zenith is < 0.03 mag in all bands, meeting one of the IAU's two recommendations for a dark site. The IAU's second recommendation, that NaD 5890/6-Å emission should not exceed in intensity the natural airglow NaD, is not met during the summer, but few spectroscopic observing programmes are likely to be significantly affected. The NaD emission brightens the sky in both V and R broad bands by about 0.07 mag. Total contamination (line + continuum) at the zenith is < 0.03 mag in U, $\approx$ 0.02 mag in B, $\approx$ 0.10 mag in V, $\approx$ 0.10 mag in R.
- The brightness of the sky shows no dependence on atmospheric extinction A_V, for $A_V <$ 0.25 mag (as is the case on 80% of nights). The sample includes two nights with $A_V >$ 0.25 mag. With A_V = 0.4 mag, the sky was brighter by $\approx$ 0.3 mag, and with A_V = 0.8 mag by $\approx$ 1.4 mag, probably because of enhanced back-scattering of streetlighting by the dust layer.

1 Introduction

The zenith brightness of the moonless night sky at a clear dark observing site, measured at high ecliptic and galactic latitudes, and during solar minimum, is typically B = 22.9 mag arcsec^{-2}, V = 21.9 mag arcsec^{-2}, about 10 million times dimmer than the daylight sky (but easily visible to the dark-adapted eye). Some published values are collected in Table 1.

The glow of the night sky comprises contributions from a number of sources, summarised in Table 2 (and reviewed by Leinert *et al* (1998) for $0.1 < \lambda < 10\ \mu$). Between the stars, the brightness of the sky is dominated by airglow and zodiacal light, and the night sky is darkest at high ecliptic latitude and low zenith distance, at solar minimum. Typical spectra of the night and twilight skies are reproduced in Figs. 1 and 2.

In the remainder of this section, we introduce the individual contributions to the brightness of the night sky. In Section 2, we report measurements of sky brightness made on La Palma. In Section 3, we compare the median dark-of-moon sky brightness at the observatory on La Palma with measurements made elsewhere; estimate the amount of light pollution; and report how sky brightness varies with time during the night, solar activity, ecliptic latitude, airmass and extinction. Conversion factors between different units commonly used for measuring sky brightness (mag arcsec^{-2}, μJy arcsec^{-2}, Rayleighs Å^{-1}, cd m^{-2}, nLamberts) are given in the Appendix.

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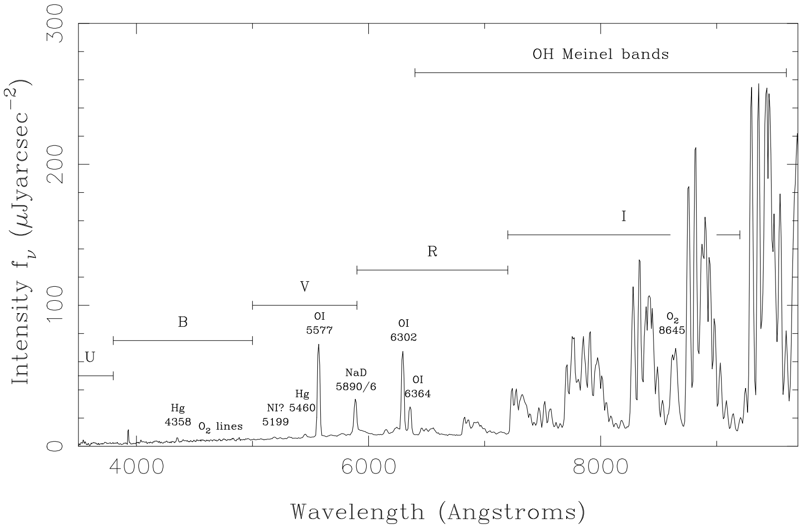

Figure 1: Typical spectrum of the La Palma sky on a moonless night, taken with the faint-object spectrograph of the William Herschel Telescope in March 1991. Most of the distinctive features of the night-sky spectrum are due to airglow. Airglow also contributes a pseudo-continuum in the blue from overlapping O_2 (forbidden Herzberg) bands (2600 - 3800 Å) and in the green from NO_2 bands (5000 - 6500 Å). The NaD emission at 5890/6 Å is partly from streetlighting, the mercury emission at 4358, 5461 Å wholly so. With the exception of the 8645-Å O_2 line, the features dominating the spectrum redward of 6500 Å are the Meinel rotation-vibration bands of OH. An atlas of the airglow 3100 - 10000 Å was presented by Broadfoot & Kendall (1968) (see also Ingham 1962). More recently, a low-resolution spectrum of the night sky was given by Louistisserand*et al* (1987) and high-resolution (0.2 Å) spectra of the wavelength range 5200 – 10600 Å were presented by Osterbrock *et al* (1996, 1997), and for $>$ 3100 Å by Vlasyuk & Spiridovna (1993). Spectra of the infrared airglow were presented by Ramsay *et al* (1992), Oliva & Origlia (1992) and Maihara *et al* (1993). The relative strengths of the lines do not reflect relative concentrations of the emitting species (NaD is bright in part because of the very short lifetime $\sim 10^{-8}$ sec of the high-energy state, so that many transitions are possible per unit time).

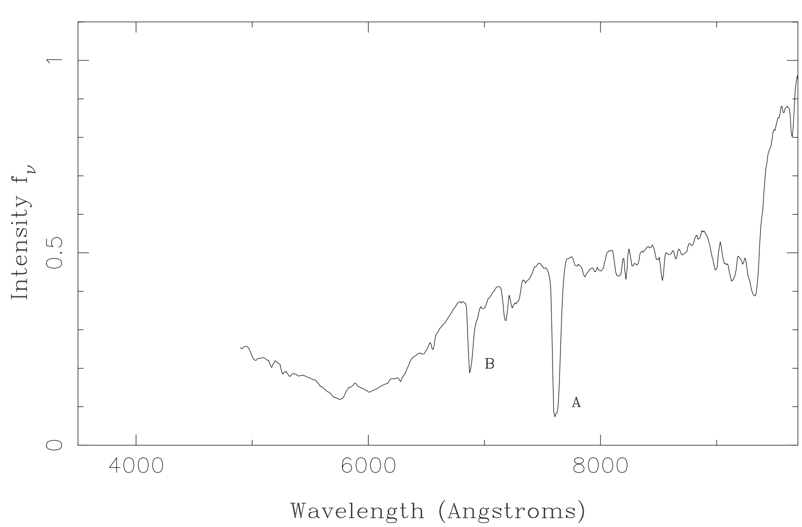

Figure 2: Typical spectrum of the La Palma sky during twilight, taken with the faint-object spectrograph of the William Herschel Telescope in March 1991. The Fraunhofer A and B bands at 7594 and 6867 Å are due to absorption by molecular oxygen in the earth's atmosphere.

Place	Nights of data	Year	$S_{10.7cm}$ MJy	U	B	V	R	I	Reference
				Sky brightness mag arcsec^{-2}					
McDonald	5	1960			22.8	21.7			Kalinowski*et al* (1975)
Junipero Serra	1	1966			23.0	21.9			Walker (1970)
San Pedro Martir	2	1970	1.5		22.9	21.9			Walker (1971)
Junipero Serra	1	1971	1.2		22.9	21.9			Walker (1973)
McDonald	6	1973	1.0		22.7	21.7			Kalinowski*et al* (1975)
San Benito	1	1976	0.7		22.9	21.9			Walker (1988)
La Silla	1	1978	1.5		22.8	21.7	20.8	19.5	Mattila *et al* (1996)
Sacramento Peak	12	1978	1.5			21.9			Schneeberger *et al* (1979)
Kottamia	1	1980	2.0		22.9	21.9		20.1	Nawar *et al* (1995)
San Benito	7	1981	2.0		22.6	21.6			Walker (1988)
Kitt Peak	7	1987	0.9		22.9	21.9			Pilachowski *et al* (1988,9)
Cerro Tololo	2	1987	0.9		22.9	22.0			Geisler (1987)
San Benito	6	1985-7	0.9		22.9	21.9			Walker (1988)
La Palma	4	1987	0.9			21.8			This paper
Cerro Tololo	1	1988	1.6		22.5	21.6			Geisler (1988)
Siding Spring		1989	2.1		22.7				Savage (1989)
Mauna Kea	16	1989-91	2.0		22.7	21.9			Krisciunas (1997)
Calar Alto	3	1990	2.0	22.2	22.6	21.5	20.6	18.7	Leinert *et al* (1995)
La Palma	9	1990-2	2.0		22.5	21.5			This paper
Cerro Tololo	1	1991	2.0	22.4					Pettini (private comm.)
Mauna Kea	8	1995-6	0.8		22.8	21.9			Krisciunas (1997)
La Palma	43	1994-6	0.8	22.0	22.7	21.9	21.0	20.0	This paper

Table 1: Near-zenith dark-of-moon broad-band sky brightness measured at various observatories. $S_{10.7cm}$ is the solar 10.7-cm radio flux density, an indicator of solar activity, measured at Ottawa (Penticton). The last five solar minima occured in 1954.5 (start of cycle 19, largest maximum on record), 1965.0 (cycle 20), 1976.8 (cycle 21), 1986.8 (cycle 22) and 1996.5 (cycle 23). Cycles 21 and 22 were of similar amplitude. As far as can be ascertained from the original references, the quoted solar-minimum sky brightnesses were measured at ecliptic latitude $> 40^o$, ecliptic longitude $> 120^o$ from that of the sun, so that variations in the zodiacal-light contribution should affect the total by < 0.1 mag. The San Benito data include faint stars ($V > 10$). The Mauna Kea data were taken with a photometer with 6.5-arcmin aperure, and may be 0.2 mag too bright due to inclusion in the beam of stars $V > 13$. The above median values for La Palma (3 ranges of dates) are based on 56 nights of data. The other 7 nights in the sample were not close to either solar minimum or maximum. The table omits any sites where light pollution is believed a priori (e.g. from the models of Garstang 1989a) to raise the sky brightness by $>\sim 0.1$ mag. Calar Alto, Lick, Lowell, Mt Wilson and Palomar are such sites.

1.1 Airglow

The airglow is emitted by atoms and molecules in the upper atmosphere which are excited by solar UV radiation during the day (Ingham 1972). Airglow is the brightest component of the light of the night sky and it contributes the main spectral features to the night-sky spectrum (Fig. 1), including the 5577- and 6300-Å lines from OI (both also prominent in the spectrum of the aurora), the ubiquitous 5890/6-Å NaD doublet (the Na may be from sea salt carried to high altitude) and the bright OH rotation/vibration (Meinel) bands in the red and IR. The atoms and molecules responsible for individual features lie in well-defined layers of the atmosphere e.g. the O_2 Herzberg bands, OI 5577 Å, NaD 5890/6 Å and the OH bands arise at an altitude of 90 - 100 km (mesopause, D layer) while OI 6300, 6364 Å and O_2 8645 Å arise at $\approx$ 300 km (F2 layer of ionosphere). The airglow lines are $\sim$ 1000 times brighter during the day.

The brightness of the airglow correlates with solar activity, e.g. with the 10.7-cm radio flux density $S_{10.7cm}$, which in turn correlates with the intensity of solar EUV radiation (100 - 600 Å) striking the upper atmosphere (Chatterjee & Das 1995). $S_{10.7cm}$ varies approximately sinusoidally during the solar cycle, from $\approx$ 0.8 MJy at solar minimum, to $\approx$ 2.0 MJy at

Contribution	Surface brightness V (S_{10} units)	Typical V_{zenith} (sunspot minimum)
Airglow	$\approx 145 + 130(S_{\odot} - 0.8)/1.2$	145
Aurora	negligible at $\lvert$latitude$\rvert < 40^o$	0
Zodiacal light	$\approx 140 - 90 sin(\lvert\beta\rvert)$ ($\lvert\beta\rvert < 60^o$) ≈ 60 ($\lvert\beta\rvert > 60^o$) (when $> 90^o$ from the sun)	60
Stars ($V > 20$, integ. light)		< 5
Starlight scattered by interstellar dust	≈ 100 exp(-($\lvert b\rvert/10^o$))	10
Extragalactic light		~ 1
Light pollution	< 20 at a 'dark' site (Smith 1979)	
		—-
Total		220

Table 2: Typical contributions to the V brightness of the moonless night sky. The unit of surface brightness S_{10} corresponds to one 10th-mag star per square degree (i.e. 27.78 mag arcsec^{-2}); 220 S_{10} corresponds to $V = 21.9$ mag arcsec^{-2}, a typical sky brightness at high ecliptic latitudes β (Table 1) (for $\beta > 40^o$ the changes are small) during solar minimum, at a site with low geomagnetic latitude. b is galactic latitude. The formula for zodiacal light is an approximate fit to the ground-based results of Levasseur-Regourd & Dumont (1980), for ecliptic longitude $> 90^o$ different from that of the sun. The formula for starlight scattered by interstellar dust is an approximate fit to the data presented by Roach & Gordon (1973). Airglow is presumed to contribute the rest of the light, and its variation with solar cycle was deduced from the ≈ 0.5 mag brightening at solar maximum (see Section 1.1). $S_{\odot}$ is the solar 10.7-cm radio flux density in MJy; it varies between 0.8 and 2.0 MJy (Section 1.1). The (small) auroral contribution peaks ≈ 2 years after the peak of the solar cycle (Roach & Gordon 1973). The zodiacal-light spectrum is approximately solar. That of the airglow is redder than solar for wavelengths > 4500 Å, i.e. the fractional contribution of zodiacal light peaks around this wavelength. The integrated light from the airglow over the whole sky corresponds to $V \sim$ -6 (cf Venus -4, full moon -13).

solar maximum (typical values; the amplitude of the solar cycle, and presumably the effect on sky brightness, varies). The sky is ≈ 0.5 mag brighter at solar maximum, judging from monitoring carried out at three sites: Hawaii 1985-96 (Krisciunas 1990, 1996, 1997); San Benito 1976-87 (Walker 1988); and La Silla 1989-93 (Leinert *et al* 1995). The La Silla data are omitted from Table 1; they were taken through a narrow-band filter.

Some dimming of the airglow might be expected after astronomical twilight, which is approximately the time at which sunset is seen from an altitude of 100 km. The 6300-Å OI emission line decays rapidly after twilight, the 5577-Å line does not. Walker (1988) reported that the B and V sky brightness at San Benito decreased by 0.4 mag during the first half of the night, with no change after midnight. Krisciunas (1990, 1997) found evidence for a small decrease during the night in the brightness of the sky over Hawaii, but using few data. Pilachowski *et al* (1989), Leinert *et al* (1995) and Mattila *et al* (1996) detected no systematic variations with time during the night at Kitt Peak, Calar Alto and La Silla respectively.

The brightness of the airglow can vary randomly, by up to a few 10s of %, with position on the sky and with time during the night (Shefov 1972, Roach & Gordon 1973, Turnrose 1974, Kalinowski*et al* 1975, Pilachowski *et al* 1989, Krisciunas 1997, Leinert *et al* 1998). Some of the variations at different wavelengths are correlated (Chamberlain 1961, Leinert*et al* 1995), e.g. the strength of the 5577-Å line correlates with that of the green/blue pseudo-continuum. The variations in intensity of the 5577-Å emission with time and position are suggestive of clouds of emitting material drifting across the line of sight at air speeds typical of the 100-km altitude. The brightness of the OH Meinel bands in the red and infrared can vary by a factor of 2 during the night, and during the year, and can show quasi-periodic variations with time (probably atmospheric oscillations, Leinert *et al* 1998). The strength of at least the NaD line varies with season; ~ 30 Rayleighs in local summer vs ~ 180 Rayleighs in winter (Allen 1973). Other complex variations with time are known. For example in winter the 6300-Å line can brighten abruptly sometime before midnight, when the ionosphere at the 'conjugate point' on the other side of the globe sees sunrise, releasing a flood of charged particles along the earth's magnetic-field lines (Ingham 1972).

The airglow is about twice as bright at geomagnetic latitude 70^o as at latitude 20^o (Allen 1973). The intensity of the 6300-Å line shows a complex dependence on geomagnetic coordinates. Roach & Gordon (1973) give a map based on measurements from a few satellite passes; the strengths in Rayleighs above different observatory locations were: La Palma 100 (the strength of the line in Fig. 1 is about 160 Rayleighs); Hawaii 400; Chile < 50; and Siding Spring < 50.

Variations in the brightness of the airglow triggered by lunar and solar tides in the atmosphere have been reported, but a recent study at La Silla found none (Mattila *et al* 1996 and references therein).

1.2 Zodiacal light

Zodiacal light is sunlight scattered by interplanetary dust. It contributes up to half the brightness of the night sky. Its intensity as a function of ecliptic latitude β and helioecliptic longitude $\lambda - \lambda_\odot$ was tabulated by Levasseur-Regourd & Dumont (1980) (earlier tabulations e.g. by Roach & Gordon 1973, overestimate the brightness by factors up to ~ 2). The Levasseur-Regourd & Dumont results agree with those obtained from space (Helios A and B) to within $\sim 10\%$ (Leinert *et al* 1998). For ecliptic longitude more than 90^o from that of the sun, the intensity varies by a mean factor ≈ 2.3 between ecliptic pole $\beta = 90^o$ and plane $\beta = 0^o$ (see Table 2). Along the plane $\beta = 0$, the intensity is minimum at helioecliptic longitude $\lambda - \lambda_\odot \approx 140^o$, rising to 3 times the polar brightness in the anti-sun direction $\lambda - \lambda_\odot = 180^o$. This weak glow in the anti-sun direction, the gegenschein, is just visible to the naked eye under good conditions, over a patch $\sim 20^o$ x 10^o along the ecliptic, with excess brightness ≈ 40 S_{10} units (James *et al* 1977). It is thought to be due to the same mechanism that causes the surge in the brightness of the moon when nearly full: the invisibility of shadowed regions on the observed object when sun, observer and object are in line. The brightness on the ecliptic may also increase slightly 60^o either side of the moon, due to scattering from dust accumulated at the earth-moon L4, L5 Lagrangian points (Kordylewski 1961, Mercer*et al* 1978). The intensity of the zodiacal light varies little with solar cycle because the luminosity of the sun in the visible waveband varies by < 1% (Lockwood *et al* 1980). There are time variations of a few % at high ecliptic latitudes due to a slight inclination of the dust-cloud's plane of symmetry with respect to the ecliptic (James *et al* 1997), and due to the eccentricity of the earth's orbit (Dumont & Levasseur-Regourd 1972). Zodiacal light dims as $R^{-2.3}$ with increasing distance R of the observer from the sun, for $0.3 < R < 3$ astronomical units (Leinert*et al* 1977), and is negligible when the sky is viewed from beyond the solar system's asteroid belt (Toller *et al* 1987).

The spectrum of zodiacial light is very similar to that of the sun over the UV - IR range (Weinberg & Sparrow 1978), and its fractional contribution to the brightness of the night sky peaks at a wavelength of 4500 Å (O'Connell 1987) (≈ 0.5 of total for $\beta = 30^o$). By 8000 Å, the brightness of the OH airglow bands has reduced the zodiacal light's fractional contribution to ≈ 0.1. In the UV, the fractional contribution falls off dramatically with decreasing wavelength, and shortward of 2500 Å, the non-airglow contribution is dominated by starlight scattered by interstellar dust. ¿From space, the sky at 2000 and 10000 Å is a factor ≈ 40 fainter than from the ground, compared with a factor ≈ 2 in the optical (O'Connell 1987).

It is important to take the contribution of zodiacal light into account when studying diurnal or seasonal variations of zenith sky brightness. For example, at typical geographical observing latitudes 20 - 40^o, the midnight sky brightness at the zenith is lowest during local summer (ecliptic low), highest during local winter (ecliptic high), mimicking a seasonal variation.

1.3 Starlight

Starlight contributes substantially to the integrated brightness of the sky; in S_{10} units:

$$\approx 25 + 250 e^{-(|b|/20^o)} \qquad (1)$$

(approximate fit to the data of Roach & Gordon 1973, b = galactic latitude). If all the starlight were scattered uniformly over the sky, it would produce a background of ≈ 100 S_{10} units. However, most of this light is from stars with $6 < V < 16$ and published measurements of sky brightness usually now refer to the sky *between* the stars. Stars fainter than $V = 20$ (easily detected in a 10-minute CCD exposure with a 1-m telescope) contribute insignificantly to the total brightness of the night sky. Starlight scattered by interstellar dust produces a diffuse glow concentrated along the galactic plane, analagous to the zodiacal light along the ecliptic (see Table 2). As noted above, for wavelengths shorter than 2000 Å, this dominates the brightness of the sky as seen from outside the earth's atmosphere (Paresce & Jakobsen 1980).

1.4 Extragalactic light

The extragalactic contribution to the brightness of the night sky is very small (Wesson 1991 explains why). Spinrad and Stone (1978) set a conservative upper limit < 5 S_{10}, and measurements from the Pioneer spacecraft, when > 3 A.U. from the sun, set an upper limit < 4 S_{10} (Toller *et al* 1987). A lower limit can be estimated from the faint galaxy counts, $B < 28$, given e.g. by Longair (1993, fig. 17) and Hogg *et al* (1997). The contribution of these to the brightness of the night sky peaks at about 0.06 S_{10} mag^{-1} for $B = 25$, with total 0.4 S_{10} for $20 < B < 28$, corresponding to ≈ 1.0 S_{10} in V band if $B - V \approx 1$. Leinert *et al* (1998) give a summary of recent upper (photometry) and lower (galaxy-counts) limits on the intensity of the extragalactic background light.

Although extragalactic light contributes only $\sim 1\%$ of the total sky brightness, its distribution on the sky is uneven (see e.g. Cole, Treyer & Silk 1992) and it may have a disproportionate effect on the signal-to-noise of observations of faint objects (e.g. Davies et al 1994). When photon noise from a smooth sky background is the limiting factor, signal-to-noise rises with integration time τ as $\tau^{0.5}$. However, a discrete object within the photometry aperture will produce an error in the measurement of intensity which is independent of τ. Since apertures are typically a few arcsec in diameter (to be > seeing), the effect becomes important for objects with a density on the sky $\sim$ (few arcsec)$^{-2}$, i.e. $V > 21$. At this level, and fainter, the object counts are dominated by galaxies rather than stars. E.g. the galaxy counts from Longair (1993) indicate that there is a probability $\sim 20\%$ of including a galaxy with $B < 24$ within a randomly-positioned aperture of size 5 x 5 arcsec^2. This will cause an error in the measured flux of a $B = 23$ target object of 40%, much greater than that due to airglow/zodiacal-light photon noise during a short dark-of-moon exposure with a 1-m telescope.

1.5 Light pollution

Light pollution at observatory sites (McNally 1994, Holmes 1997) arises principally from tropospheric scattering of light emitted by sodium- and mercury-vapour and incandescent street lamps.[2] Typical street-lamp spectra were presented by Osterbrock *et al* (1976). The 4358-Å Hg line can be a hazard for observers wanting to compare the intensities of the 4363 and 5007-Å OIII lines (for measuring the temperature of astrophysical plasmas). The 5460-Å Hg line lies in the centre of the y band of the *ubvy* system. The NaD 5890/6-Å line typically contaminates both the V and R passbands. Models of the contribution of city lighting to dark-sky brightness were presented by Treanor (1973), Walker (1973), Yocke *et al* (1986) and Garstang (1984, 1986, 1989, 1991a,b,c). Walker (1977, 1991) and Garstang (1989) estimate the increase in brightness at zenith distance 45^o, in the direction of a conurbation of population P at distance D km to be $\sim PD^{-2.5}/70$ mag. The sky near the horizon is brightened in directions both towards and away from a source of light pollution (Berry 1976). The IAU recommendations for a dark site are continuum $\Delta mag < 0.1$ for $3000 < \lambda < 10000$ Å, and intensity of NaD light pollution < that from airglow, at $ZD = 45^o$ towards any city (Smith 1979, appendix 4.1 of McNally 1994).

[2]Lighting wastefully emitted above the horizontal costs the US taxpayer $\sim \$10^9$ year^{-1}, more than the cost of funding US astronomy (Hunter & Crawford 1991).

1.6 Moonlight

Moonlight brightens the sky by about 1 mag (quarter moon, phase 0.5) to 4 mag (full moon) in U, B and V. The brightening is less dramatic in the red, $\approx$ 2 mag in I at full moon. The moonlit sky brightness depends strongly on a number of parameters. A model of sky brightness as a function of lunar phase, lunar zenith distance, distance from the moon etc. was presented by Krisciunas & Schaefer (1991). In this paper, we consider only the brightness of the moonless sky.

1.7 The effect of airmass

At high airmass, light from outside the atmosphere may be dimmed by scattering and absorption, but the airglow will probably be brighter, since a line of sight intercepts a larger number of atoms in the airglow layer. For airglow arising in a thin layer at height h, the intensity should vary with zenith distance ZD as

$$I(ZD) = I(0)/\sqrt{1 - (a/(a+h)^2 sin^2 ZD)} \tag{2}$$

where a is the radius of the earth (van Rhijn 1921). (The dependence on zenith distance of the intensity of a given emission line can be used to determine the height of the airglow species responsible.) $I(ZD) \approx$ airmass $\approx \sec(ZD)$ for $ZD < 70$ deg. If a fraction f of the sky brightness is due to airglow, one expects the sky to be

$$\Delta(ZD) = 2.5 log_{10}((f * I(ZD) + (1-f) * I(0))/I(0)) \tag{3}$$

mag brighter at zenith distance ZD compared with zenith. For $f = 0.7$ (solar minimum), this predicts $\Delta(ZD) = 0.04, 0.11, 0.20, 0.34, 0.54$ mag at $ZD = 20, 30, 40, 50, 60$ deg. The values of $\Delta(ZD)$ are $\approx$ 10% higher at solar maximum ($f = 0.8$). Close to the horizon, the airglow is dimmed by scattering and absorption; it is brightest at a zenith distance of about 80^o (see James *et al* 1997 for an example of a specific measurement).

Mattila *et al* (1996) observed the 1978 La Silla sky brightness to be about 0.05 mag brighter at $ZD = 30^o$ than at the zenith, while Leinert *et al* (1995) reported that at Calar Alto in 1990, the sky was 0.1 mag brighter at $ZD = 40^o$. These two measurements are broadly consistent with the prediction of equation (3) above.

1.8 The effect of dust

Dust suspended in the atmosphere absorbs and scatters incoming light. The darker parts of the sky can thus be brightened by scattered zodiacal light (from the ecliptic) and starlight (from the Milky Way) by up to a few 10s of % (Leinert *et al* 1998), or by moonlight (several magnitudes, as mentioned above). More importantly, dust backscatters streetlighting, the spacebound flux from which may be comparable in intensity with inbound extraterrestrial light and airglow, $\sim$ 10 Wkm^{-2} over the visible range (see Section 3.6 and Table 5). Garstang (1988, 1991a,b) presented models of the effect of dust on light pollution.

2 Measurements from La Palma

La Palma in the Canary Islands hosts Europe's largest Northern-hemisphere observatory, the Observatorio del Roque de los Muchachos (Murdin 1985). The observatory lies close to the island's peak, on the rim of a large volcanic caldera, at longitude 18^o W, latitude 29^o N, altitude 2300 m, geomagnetic latitude $\approx 20^o$ N. Approximately 70% of the nights are clear (95% in the summer) and 60% are photometric. The median site seeing is $\approx$ 0.7 arcsec (Muñoz-Tuñon *et al* 1997). Atmospheric extinction is typically 0.15 mag in V, but can be substantially higher during the summer (Figs. 3,4), when dust from the Sahara desert (400 km away) blows over the Canary Islands. The island has a population of $\approx$ 80000 people, but light-pollution is strictly controlled.

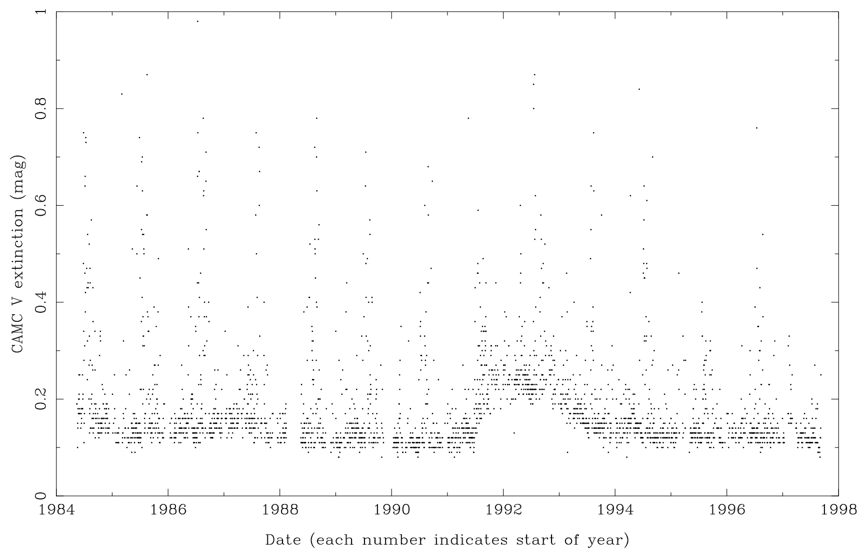

Figure 3: Variation of extinction, as revealed by nightly measures made at the Carlsberg Automatic Meridian Circle during 1984-96 (CAMC 1997). Saharan dust is responsible for the high values of extinction measured during the summer (July to September). The summer peaks in extinction seen at La Silla have a different cause (Burki *et al* 1995). The ≈ 0.1 mag rise in extinction in 1991 - 93 is due to dust injected into the atmosphere by the eruption of Mt. Pinatubo in the Philippines (noted also at other observatories e.g. by Burki *et al* 1995, Forbes *et al* 1995).

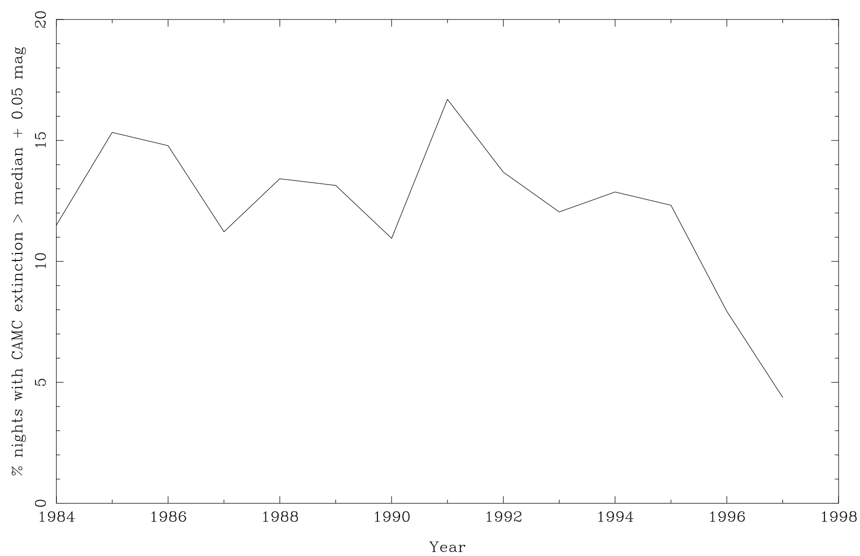

Figure 4: Recent (> 1995) decline in the fraction of dusty nights at the observatory, a night being considered dusty if the extinction A_V measured at the Carlsberg Automatic Meridian Circle is greater than (running median + 0.05) mag, the median being that of the current month plus 3 months either side, but excluding July, August, September.

Dark-of-moon sky brightness was measured from images in the electronic data archive of the Isaac Newton Group of telescopes. This archive includes all digital (mainly CCD) data taken with the 4.2-m William Herschel, 2.5-m Isaac Newton and 1.0-m Jacobus Kapteyn Telescopes. It currently (1997) comprises $\approx$ 430000 CCD exposures, $\approx$ 50% of which are direct images. Most of the direct images are taken through broad-band U, B, V, R or I filters (very few in Z) with the 2.5-m or 1.0-m telescopes. The 4.2-m telescope is used mainly for spectroscopic work. For this study, only images taken with the moon below the horizon and during astronomical night (sun at least 18^o below the horizon) were used. We concentrated on nights when several observations had also been made of photometric standard stars, and avoided periods when poor observing conditions were logged. Nights on which the Carlsberg Automatic Meridian Circle did not record a measure of extinction (usually because the night was not photometric) were excluded. Most of the data are drawn from the solar-minimum years 1994-6, but we also sampled the other years ($>$ 1987) covered by the archive. In all, we measured the background brightness on 397 images taken on 58 nights with the Isaac Newton Telescope and 30 images on 5 nights with the Jacobus Kapteyn Telescope.

Sky brightness was measured in areas apparently free of nebulosity, stars, cosmic-ray events or CCD defects. Photometic calibration was obtained from the archived observations of standard stars (usually from the list of Landolt 1992) on the same night. Sky brightness was calculated for each band, as follows:

Counts sec^{-1} from each standard:

$$ST = (counts - sky - bias)/\tau_{ST} \tag{4}$$

Zeropoint (apparent mag for 1 count/sec):

$$ZST = m_{app} + ext + 2.5log_{10}(ST) \tag{5}$$

Counts sec^{-1} pixel^{-1} from sky:

$$SK = (counts - bias)/\tau_{SK} \tag{6}$$

Sky brightness in mag arcsec^{-2}:

$$SKYBR = ZST - 2.5log_{10}(SK/scale^2) \tag{7}$$

where *sky* is the sky-background level on the exposures of standards; *bias* is the CCD bias level; *counts* and *bias* are within an aperture for the standard, and per pixel for sky; τ_{ST} and τ_{SK} are the exposure times on standards (typically a few seconds) and sky (typically 200 - 1000 seconds); m_{app} is the catalogue apparent magnitude of the standard star in the relevant band; *ext* is the atmospheric extinction in magnitudes for the standard star (airmass x zenith extinction); and *scale* is the angular scale at the CCD (between 0.3 and 0.6 arcsec/pixel). In equation (5) the mean zeropoint ZST for the given band for the night was used. Note that the standard-star magnitudes have been corrected for extinction, the sky brightnesses have not, following the convention adopted in most of the recent studies of sky brightness (e.g. by Walker 1988, Krisciunas 1990, Lockwood *et al* 1990, Leinert *et al*1995, and Mattila *et al* 1996). Correcting the sky brightness for extinction would be appropriate only if the extinguishing layer were known to be below all sources of sky brightness, which is not the case; and would be feasible only if the relative amounts of extinction due to absorption (affecting light from stars and sky) and scattering (affecting only light from stars) were known.

To minimise the amount of data-reduction required, the CCD images were not flat-fielded. On the EEV and TEK CCDs in use during this period, the rms sensitivity variations are about 5% pixel to pixel and over larger areas. Since the sky brightness measurements were averaged over many pixels, and the counts from the standard stars were typically spread over $\sim$ 10 pixels, omission of flat-fielding introduces errors $<\sim$ 5% into the measurements of sky brightness. To exclude non-photometric nights, data were discarded if the rms on the zeropoints for the standard stars was $>$ 0.2 mag in any band, or, in a few cases, if the measured zeropoint was grossly different from that obtained with the same instrument/detector combination on other nights. The zeropoint for a given CCD is stable to $<$ 10% from night to night.

The analyses reported in the following sections are based on 427 sky-brightness measurements and 451 observations of standard stars, made during 63 nights at the Isaac Newton and Jacobus Kapteyn Telescopes.

3 Results

As noted in the introduction, sky brightness depends significantly on a number of parameters, and these dependencies may differ from site to site. The large size of the dataset described in Section 2 helps in disentangling these dependencies for La Palma, and also in averaging out the effects of short-term variations in airglow noted in previous studies. In each of the analyses below, all but one of the following criteria (depending on the parameter being investigated) have been used in isolating a small subset of clean data (plotted in each accompanying figure) from the full set: date of observation later than 1994.0 (for solar minimum); ecliptic latitude $> 40^o$ or $> 30^o$; galactic latitude > 10 deg; zenith extinction for night < 0.2 mag; airmass < 1.4. This selection limits to < 0.1 mag the effect on sky brightness of the variation of any individual parameter. Quoted values of sky brightness are medians rather than means, and quoted errors on the median are $dx/\sqrt{N}$ where $\pm dx$ includes 2/3 of the points, and N is the number of points.

3.1 Mean night-sky brightness and variation with solar cycle

La Palma sky brightness is plotted against date in Figs. 5 - 8. The median values (of the high-ecliptic-latitude data represented by stars) during solar minimum 1994-6 are $B = 22.7 \pm 0.03$, $V = 21.9 \pm 0.03$, $R = 21.0 \pm 0.03$ mag arcsec^{-2}, with a scatter of about 0.15 mag in each band. A few measurements in V are also available from 1987 (previous sunspot minimum) with median $V = 21.8$ mag arcsec^{-2}. The brightnesses in V and R are similar to those measured at the other sites listed in Table 1 (mostly in the Americas). The measured brightness in B is 0.2 mag higher than the pre-1990 data in Table 1, but the median is dominated by 1995 data, and is consistent with a trend found by Krisciunas (1997) from 14 measurements at Mauna Kea during 1993-6, showing a steady decline from 22.3 to 22.9 mag arcsec^{-2} over this period, i.e. the B sky brightness was not at a minimum in 1995 even though the 10.7-cm radio intensity of the sun was at a minimum throughout 1994-6. (The relatively brighter sky in B is unlikely to be due to light pollution, which affects mainly the V and R bands.) The 0.15-mag scatter in the measured values is a combination of measurement errors (inaccurate extinction values, lack of flat-fielding) and true variations in sky brightness.

Although these data sample only sparsely the period of solar maximum $\approx$ 1990, an enhancement of sky brightness at that time is evident in Fig. 8, which includes both the B and V data, corrected for the contribution from zodiacal light. The sky was 0.4 ± 0.1 mag brighter in 1990 than in 1995. In R, the large variations in airglow intensity mask any changes with solar cycle, but assuming that the relative contributions of airglow and zodiacal light in V given in Table 2, that the brightness of the R airglow is proportional to that in V, and that the zodiacal light has the spectrum of a 6000-K blackbody, the predicted variation in total R sky brightness with solar cycle is ≈ 0.5 mag. No measurements were made close to the time of the Pinatubo (1993.5) volcanic eruption, but the sky probably brightened then by a few tenths of a mag (Krisciunas 1996).

There are fewer measurements in U and I bands; the median sky brightnesses are $U \approx 22.0$, $I \approx 20.0$ mag arcsec^{-2}, broadly consistent with the few values measured elsewhere (Table 1). The I brightness is dominated by OH (Meinel) emission bands (Fig. 1) and varies by up to a factor ~ 2 during the night.

3.2 Variation of sky brightness with time during the night

La Palma sky brightness is plotted against time after astronomical twilight in Fig. 9.

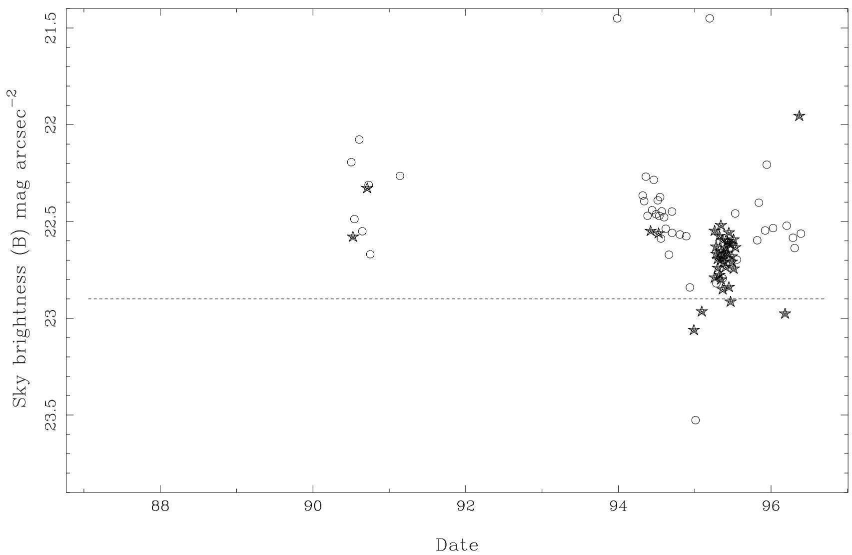

Figure 5: La Palma B sky brightness vs date. Stars represent data satisfying the following criteria: ecliptic latitude > 40 deg; galactic latitude > 10 deg; airmass < 1.4; mean V extinction during the night < 0.2 mag; at least one photometric standard observed that night; rms on standards < 0.15 mag; Tektronix or EEV CCD. Circles represent data satisfying similar criteria but with ecliptic latitude $\beta < 40^o$ (i.e. contaminated by zodiacal light). The plotted points have been given a small random scatter along the abcissa to reduce overlap. On this and succeeding figures, points falling outside the graphed area are plotted at the appropriate edge (or corner). The dashed line indicates typical solar-minimum sky brightness measured at other observatories (from Table 1).

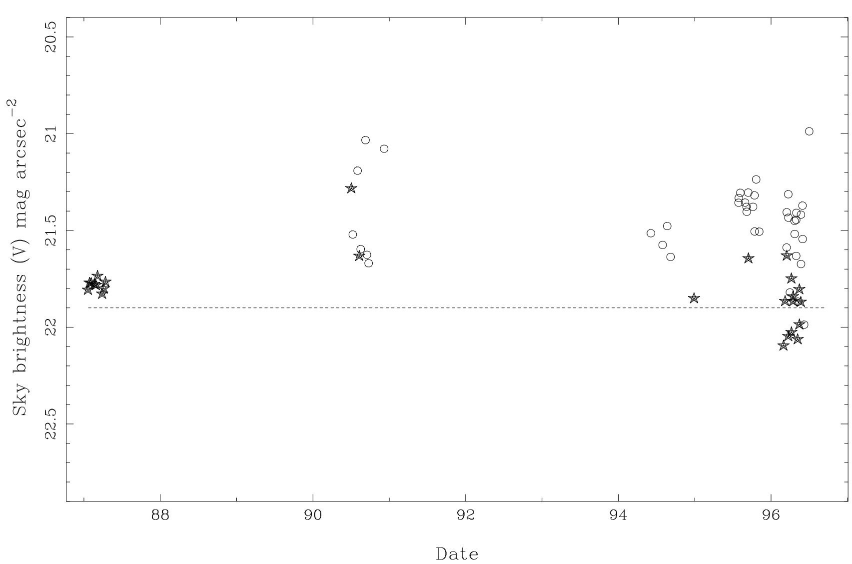

Figure 6: La Palma V sky brightness vs date. Symbols are as for Fig. 5.

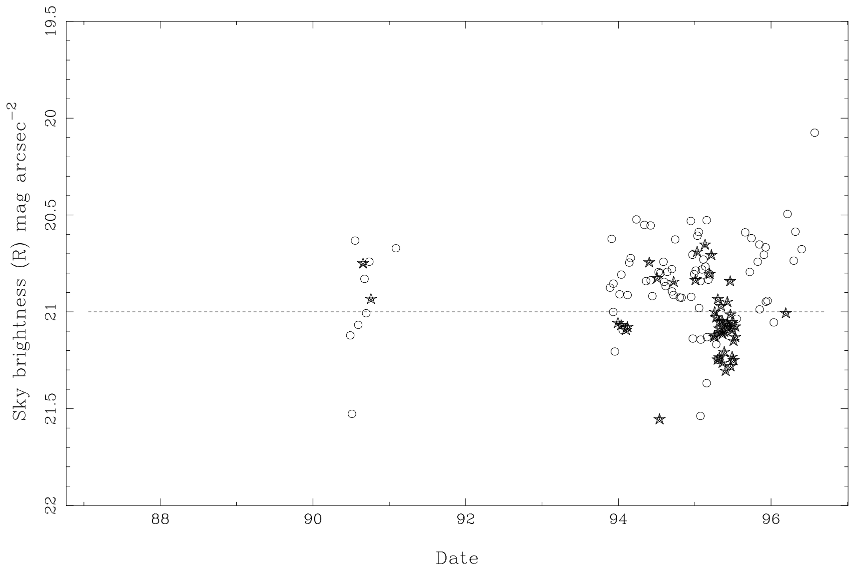

Figure 7: La Palma R sky brightness vs date. Symbols are as for Fig. 5.

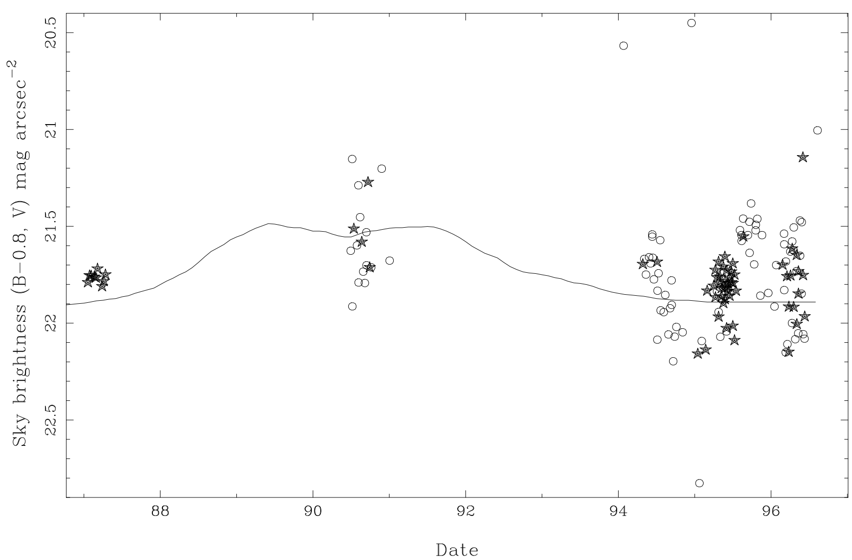

Figure 8: La Palma combined $B - 0.8, V$ sky brightness (i.e. data from Figs. 5 and 6) vs date. In this and succeeding figures, the measured sky brightnesses have been corrected for zodiacal light in order to reduce the scatter: the formula given in Table 2 has been used to normalise the sky brightnesses to ecliptic latitude $\beta = 40^o$ (the size of the corrections applied is < 0.2 mag). The curve indicates the variation of sky brightness expected with solar activity, using the $S_{10.7cm}$ flux density as an indicator of solar activity, and assuming a total range of 0.4 mag. Symbols are as for Fig. 5.

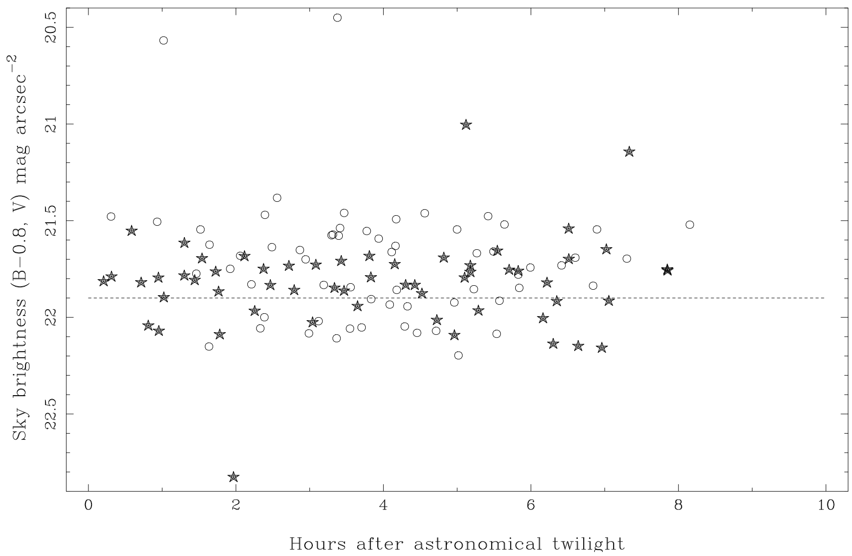

Figure 9: La Palma sky brightness vs time after astronomical twilight. Stars: data taken after 1994.0, ecliptic latitude $> 30^o$ and satisfying the other criteria given in the caption of Fig. 5. Circles: data satisfying similar criteria but with $\beta > 30^o$. A correction has been made for the varying contribution of zodiacal light (see caption of Fig. 8).

The difference between the sky brightnesses at the beginning and end of the night is 0.03 $\pm$ 0.07 mag, consistent with zero. A similar plot against hours before dawn astronomical twilight provides no support for the idea that the sky is darkest before dawn. These results contrast with the finding by Walker (1988) that the sky brightness at San Benito dimmed by $\approx$ 0.4 mag in B and V during the first half of the night. However, some of the variation he saw might be due to the diminishing contribution of zodiacal light at the zenith. This effect is particularly pronounced in the spring, when Walker observed, because at zenith both ecliptic latitude and helioecliptic longitude increase after astronomical twilight, and the zenith brightness will diminish by $\approx$ 0.25 mag during the first half of the night (assuming the zodiacal-light distribution measured by Levasseur-Regourd & Dumont 1980). Walker noted this possibility but thought the intensity of the zodiacal-light varaiations too small to account for the effect he observed.

After astronomical twilight, the prominent 6300-Å line diminishes rapidly in intensity, e.g. on 24 June 1995 from 150 Å to 30 Å equivalent width. This implies a small ($<\sim$ 0.1 mag) diminution in the broad-band R sky brightness. No variation $>$ 0.1 mag is visible in a plot of R sky brightness against time after twilight.

3.3 Variation of sky brightness with ecliptic coordinates

La Palma sky brightness is plotted against ecliptic latitude β in Fig. 10. The variation observed (0.4 mag brighter on the ecliptic than at the poles) is consistent with that predicted by the formula given in Table 2 (solid curve).

10 measurements were made at $|\beta| < 5$ deg. One of these lies in the expected region of the gegenschein between 170 and 190^o in longitude from the sun. It is 0.3 mag brighter than the median of the other 9, consistent within the errors with the 0.2 mag brightening expected in the antisun direction (Section 1.2).

3.4 Variation of sky brightness with galactic latitude

Few ($<$ 2%) of the archive images examined were taken at galactic latitude $b < 30^o$, For $b > 30^o$, there is no significant variation ($<$ 0.1 mag) with b, consistent with the $\approx$ 0.05 mag variation expected from the formula given in Table 2 for starlight scattered by interstellar dust.

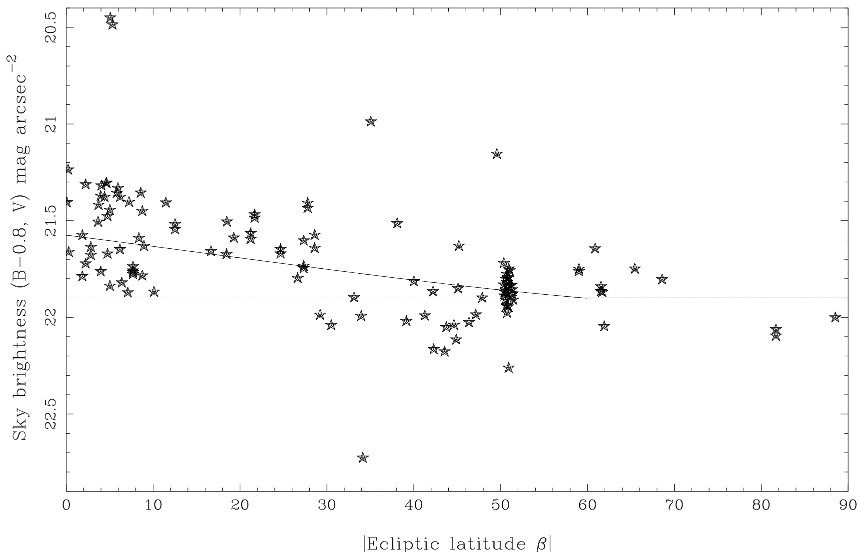

Figure 10: La Palma sky brightness vs |ecliptic latitude β|. Stars: measurements made after 1994.0, and satisfying the other criteria given in the caption of Fig. 5, except that relating to ecliptic latitude. The solid curve indicates the brightness variation predicted by the formula given in Table 2.

3.5 Variation of sky brightness with airmass

La Palma sky brightness is plotted against airmass in Fig. 11. The sky is 0.25 +- 0.07 mag brighter at airmass $\sim$ 1.5 than it is at the zenith. Equation (3) can be used to deduce from this the fraction of the sky brightness due to airglow, $f = 0.6 \pm 0.15$, consistent with that assumed in Table 2 ($f = 0.7$ at solar minimum).

3.6 Light pollution

80000 people live on La Palma, mostly in or near nine small towns lying between 10 and 15 km from the observatory (Rodriguez *et al* 1990). Other possible sources of light pollution include the neighbouring islands of La Gomera, El Hierro and Tenerife (which has floodlit tourist beaches). There is a direct line of sight from the observatory to sea level on all three islands (line-of-sight range to sea level $\approx 120\sqrt{A}$ km, where A is the altitude of the observer in km). Clouds lying below the observatory often blot out streetlighting, although during the summer months they tend to be dispersed by warm winds. Azimuths (north through east), populations and distances of potential light-polluting communities are summarised in Table 3. There are no important sources of light pollution north and west of the observatory. The last column of Table 3 gives Δmag_G, the increases in sky brightness predicted by the models of Garstang (1989) for the given populations and distances. These are based on an average 1000 lumens illumination person^{-1}. The actual value for La Palma is $\approx$ 1500 lumens person^{-1}, but much less of the latter escapes into the sky than for a typical US city; the calculated Δmag_G serve mainly to indicate approximate relative amounts of light pollution expected in different directions.

Orange glows are visible to the naked eye at azimuths $\approx$ 50, 120, 190. The most *luminous* contributor is the island of Tenerife, but visual inspection of the horizon confirms what Table 3 suggests, that the glow in this direction is not particularly bright, and that lighting on Tenerife does not threaten the quality of the La Palma sky. Most of the contaminating light is from La Palma's 14000 streetlamps, which consume $\approx$ 2 MW of electrical power and emit $\approx$ 120 Mlumens, $\sim$ 180 kW, of visible light (see Appendix for conversion factors). Approximately half of the light generated emerges from the lamp housing, and $\approx$ 10% of the emerging light is reflected from the ground, so $\approx$ 9 kW, or $\sim$ 10 Wkm^{-2} (island area = 700 km^2) escapes to the sky. This is comparable with the inbound light of the night sky, $\sim$ 10 W km^{-2} (see Table 5), so that significant back-scattering by the atmosphere constitutes

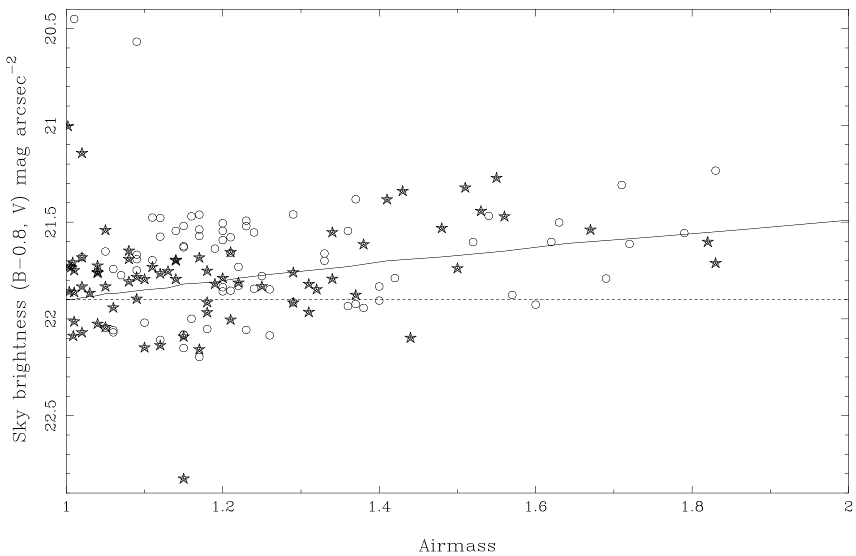

Figure 11: La Palma sky brightness vs airmass. Stars: measurements made after 1994.0, ecliptic latitude $> 30^o$, and satisfying the other criteria given in the caption of Fig. 5, except that relating to airmass. Circles: data satisfying similar criteria but with $\beta > 30^o$. A correction has been made for the varying contribution of zodiacal light (see caption to Fig. 8). The solid curve indicates the variation in sky brightness predicted by equation (3) with $f = 0.7$.

Place	Azimuth ^{o}	Population (1986)	Distance km	Δmag_G
Barlovento	50	3000	10	0.06
Los Sauces / San Andres	110	6000	12	0.08
Tenerife	115	600000	130	0.02
Santa Cruz	125	18000	15	0.18
Brena Alta/Baja	140	8000	15	0.08
La Gomera	140	17000	90	<0.01
El Paso	180	7000	12	0.10
El Hierro	190	7000	110	<0.01
Los Llanos / Tazacorte	200	23000	12	0.32

Table 3: Possible sources of light pollution at the observatory on La Palma. The estimated changes in zenith sky brightness given in the last column are from the model of Garstang (1989a). They are likely to be overestimates (see text) but give a rough idea of the relative contributions to be expected from different sources.

a light-pollution hazard. The fractional illumination provided by each type of lamp is given in Table 4.

Type of lamp	Philips brand	Flux %	Contamination of sky brightness (mag) U 3200-3800Å	B 3800-5000Å	V 5000-5900Å	R 5900-7200Å
Sodium low-pressure	SOX	49	0	0	0.05	0.04
Sodium high-pressure	SON-T	21	0	<0.01	0.03	0.02
Mercury	HPL-N	13	<0.03	0.02	0.01	0.02
Incandescent		15	< 0.01	< 0.01	0.01	0.02
Total			<0.03	0.02	0.10	0.10

Table 4: Contamination of the sky above the observatory by streetlamps on La Palma. The first 3 columns give the lamp type, commonest Philips' serial and fraction of total lumens illumination on La Palma (information supplied by Javier Diaz of the Oficina Técnica para la Protección de la Calidad del Cielo). Fluorescent lamps contribute a negligible fraction of the total illumination, ≈ 2%. Columns 4 - 7 give the brightening of the sky above the observatory in mag for line plus continuum emission from the lamps, as estimated in Section 3.6. The effect of NaD emission on the brightness of the sky in V and R is less than it otherwise might be because the line enters near the edge of the passbands in both cases (typically ≈ 0.6 x maximum in V, ≈ 0.75 $*$ maximum in R for the passbands used for the observations described in this paper).

A royal decree of 1992 (La Ley del Cielo, reproduced in appendix 6 of McNally 1994) strictly limits outdoor night-time illumination on La Palma. Low-pressure sodium lamps must be used except in urban areas; the fraction of ultraviolet light emitted by lamps is limited; discharge-tube illumination, and most high-pressure sodium lamps, must be extinguished after midnight. Lamps must not emit light above the horizontal, so only the ≈ 10% of the light reflected from the ground (snow does not fall on the streetlit parts of the island) escapes into the sky. Between 1992 and 1997, the estimated amount of light escaping into the sky has decreased by 20% as a consequence of an ongoing programme to improve the efficiency and shielding of public lighting (Javier Diaz, private communication).

The V-band zenith sky brightness on La Palma is similar to that at other dark sites (Table 1), which suggests that light pollution must contribute $\sim< 0.1$ mag to the total. Sky brightness is plotted against azimuth in Fig. 12. The raw data show considerable brightening in the south, but as can be seen from Fig. 12, this brightening disappears after the measuerments are corrected for the contribution of zodiacal light, and there is no discernible peak in sky brightness at any particular azimuth.

A much stronger limit on the contribution of light pollution to the brightness of the sky may be obtained from the equivalent widths of the NaD and Hg lines in the spectrum of the zenith night sky. These yield directly the contribution to sky brightness from emission lines, while that from broad and continuum features can be inferred from the strengths of the emission lines, the known shapes of the lamp spectra (given e.g. by Osterbrock 1976, and in the Philips Catalogue of Lamps), and the relative numbers of lamps of different kinds. The median equivalent widths of the NaD 5890/6, Hg 5460 and Hg 4358 Å lines at solar minimum (when the continuum is faintest) during summer (when the airglow NaD is dimmest) are 100, 7 and 9 Å respectively, although they vary by a factor of ~ 1.5, probably due to changing cloud cover below the observatory (as found at Palomar, see Turnrose 1974), which often blots streetlighting from view. The equivalent width shows no significant variation with zenith distance for $ZD < 45^o$. Below are derived estimates of contamination in each of the bands U, B, V and R (negligible in I, where sky brightness is dominated by the OH airglow). The results are summarised in Table 4.

Low-presure sodium lamps

Nearly all the light from these lamps emerges in the NaD 5890/6-Å doublet and is passed by both V and R filters. There is weak narrow line emission at 5683/8 and 6154/61 Å, and negligible emission in the continuum. The NaD emission from the sky is a mixture of light pollution and airglow, so the observed equivalent width sets an upper limit of ≈ 0.07 mag to the contribution to the V band and ≈ 0.06 mag to the R band. The absence of detectable

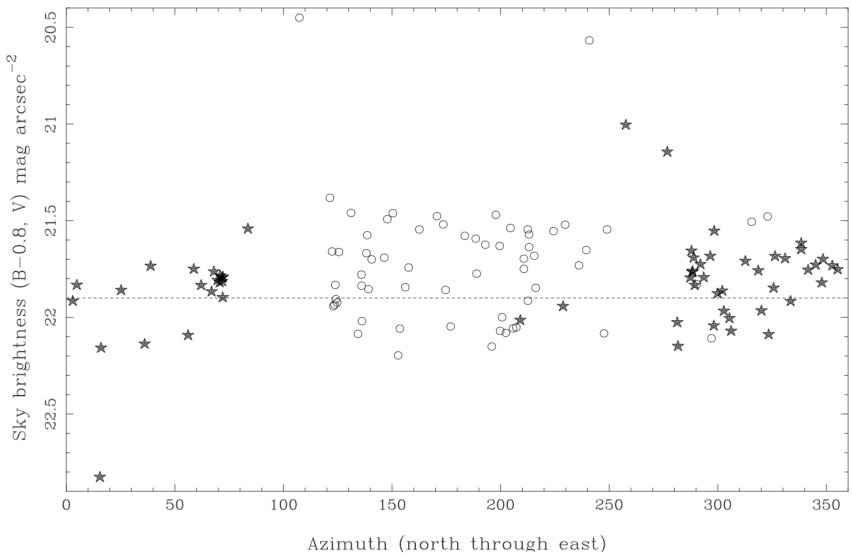

Figure 12: La Palma sky brightness vs azimuth. Stars: measurements made after 1994.0, ecliptic latitude $> 30^o$, and satisfying the other criteria given in the caption of Fig. 5. Circles: data satisfying similar criteria but with $\beta > 30^o$. A correction has been made for the varying contribution of zodiacal light (see caption to Fig. 8); without this correction, the sky appears brighter in the south because of the lower mean ecliptic latitude (reflected in the preponderance of data represented by circles). A similar plot for airmass > 1.4 is sparsely populated (see Fig. 11) but shows no dependence of sky brightness on azimuth.

5683/8 emission does not place a useful limit on the strength of the NaD emission because of the relative weakness of the former.

An opportunity to separate the airglow and light-pollution NaD contributions arose on the night of 24/25 June 1995, when the Instituto de Astrofisica de Canarias arranged for most of the $\sim$ 100000 street lamps on the four western Canary islands (La Palma, Tenerife, La Gomera and El Hierro) to be switched off for 1 hour starting at local midnight, to celebrate the 10th anniversary of the inauguration of the observatories. The observer at the William Herschel Telescope that night (Ian Waddington) happened to be taking near-zenith low-resolution spectra covering most of the visible range. ¿From these it was possible to extract spectra of the moonless sky before, during and after the blackout (Fig. 13).

The equivalent widths of the NaD line before and during the blackout were 75 and 30 Å respectively. At this wavelength, with the zenith sky brightness given in Table 2, an equivalent width of 30 Å corresponds to 30 Rayleighs (see Appendix), in agreement with the 30 Rayleighs given by Allen (1973) for the summer strength of the NaD line. Thus, of the 100-Å median observed equivalent width of the NaD line during the summer, $\approx$ 70 Å (70 Rayleighs) is due to street lighting, corresponding to an increase in sky brightness of $\approx$ 0.04 mag in both V and R bands (equivalent width / bandwidth x relative filter transmission at 5893 Å).

High-pressure sodium lamps

These lamps have a pinkish colour. Most of the light is emitted in a broad NaD line with FWHM 400 Å and a deep central reversal. There is significant continuum emission between 5500 Å and the infrared, and narrow emission lines at 4665/9 (violet), 4979/83 (blue), 5149/53 (blue), 5683/8 (green) and 6154/61 (red) Å. The absence of any broad NaD feature in the night-sky spectrum limits the contribution to the V and R bands to $<$ 0.08 mag. The absence of detectable 5683/8 places a similar limit on the contribution from the broad feature, $<$ 0.09 mag. Contributions from other features are very small, $<$ 0.01 mag. A stronger constraint can be placed knowing that the ratio of the illuminating contributions from high- and low-pressure sodium lighting on La Palma is $\approx$ 0.4 (Table 4). Taking into account the higher transmission by V and R filters of the broadened NaD emission, this means that light pollution from the high-pressure lamps must contribute $\approx$ 0.03 mag in V and $\approx$ 0.02 mag in R.

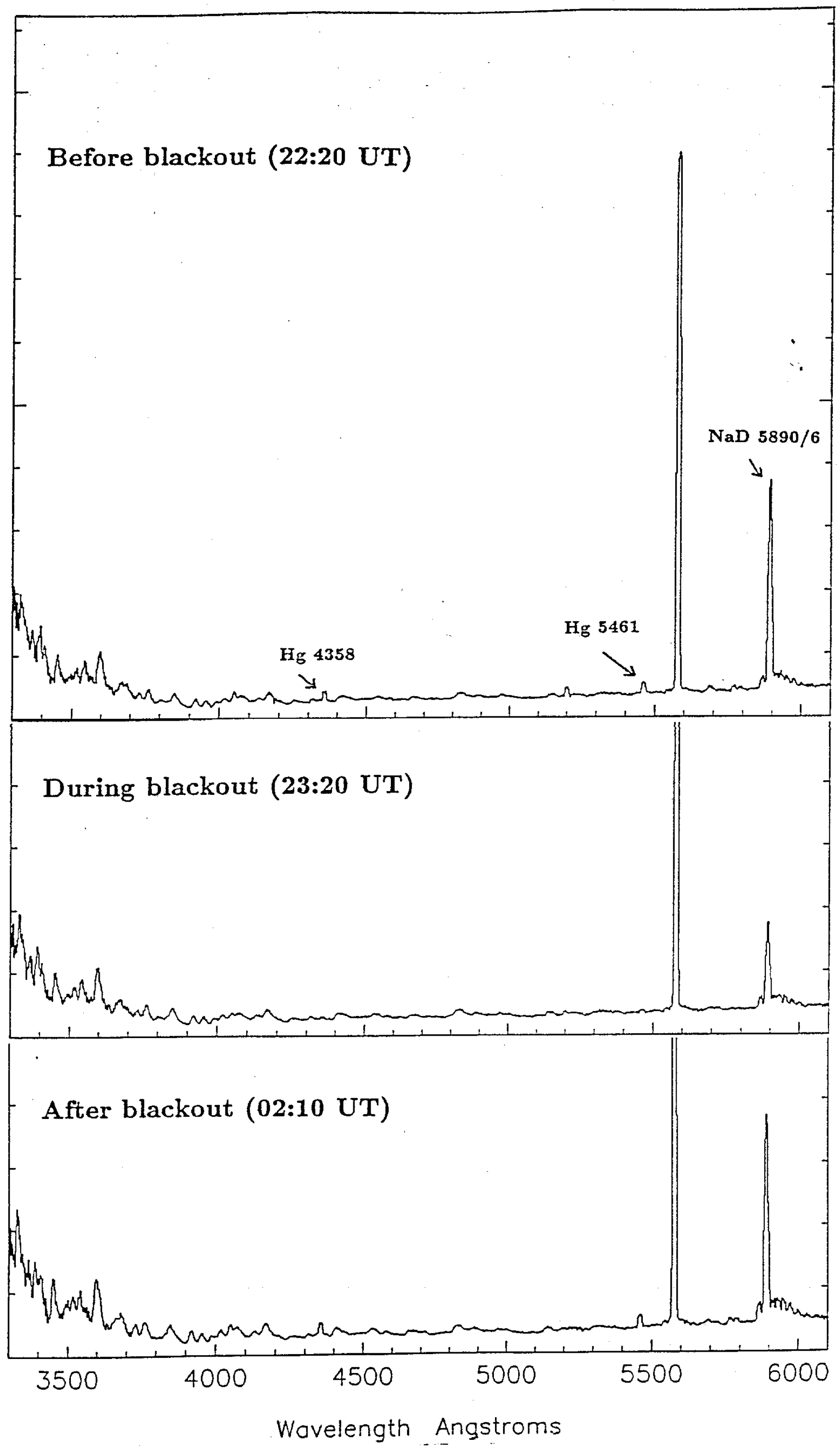

Figure 13: Spectra of the La Palma night sky before, during and after the 1-hour blackout of 25 June 1995. Note the disappearance of the Hg lines, and partial disappearance of the NaD line during the blackout (not all the streetlamps were switched on again afterwards). The NaD emission remaining during the blackout is airglow. The brightness of the continuum changed by < 0.03 mag when the blackout commenced.

Mercury lamps
Mercury lamps have narrow lines at 3651/63, 4047, 4358, 5461, 5770 and 5791 Å, and broad features at 6200 and 7000 Å (FWHM $\approx$ 100 Å, from the phosphor used to convert UV to visible). There is also weak continuum emission over the whole visible range. The 4358 and 5461 Å lines are visible in the spectrum of the La Palma night sky. The results in Table 4 are based on the measured equivalent widths of these lines and the known shape of the lamp spectra. The value derived in V is consistent with the ratios given in the third column.

Incandescent lamps
The contribution of incandescent lamps (continuum only) to the brightness of the night sky in V can be estimated only from the lumen ratios in column 3 of Table 4. Knowing the shape of the continuum spectrum (black body, $\approx$ 3200 K), the contributions by incandescent lamps in other bands follow. The 25 June 1995 blackout (discussed above) provided an additional limit < 0.03 mag on the contribution in B and V.

In summary, light pollution contributes < 0.03 mag to the zenith continuum sky brightness in all bands (Table 4), well below the IAU recommendation of < 0.1 mag at $ZD = 45^o$, (see Section 1.5) for a dark observing site. The strength of the typical NaD 5890/6-Å light pollution, $\sim$ 70 Rayleighs, exceeds that due to natural airglow radiation (the limit recommended by the IAU for a dark site) during the summer. However, few spectroscopic observing programmes are likely to be adversely affected by this contamination. Streetlamp emissions in the Hg and NaD lines raise the broad-band V and R sky brightnesses by 0.09 and 0.08 mag respectively. The total contamination is < 0.03 mag in U, $\approx$ 0.02 mag in B, $\approx$ 0.10 mag in V, $\approx$ 0.10 mag in R.

This degree of light pollution is comparable to that at Kitt Peak, $\sim$ 0.02 mag in B, 0.05 mag in V in 1988 (Massey *et al* 1990) from Tucson (275000 inhabitants, 65 km distant). It is less than that at Calar Alto, $\sim$ 0.2 mag in V (Leinert*et al* 1995) from Almeria (160000 inhabitants, 45 km distant). It is more than that at La Silla, probably $<\sim$ 0.02 mag (Mattila *et al* 1996) from Vallemar (38000 inhabitants, 65 km away) and La Serena (160000 inhabitants, 150 km away).

3.7 Variation of sky brightness with extinction

On La Palma, extinction is high during the summer months when a pall of neutral-extinction Saharan dust hangs over the islands (Whittet, Bode & Murdin 1987, Moulin *et al* 1997), see Figs. 3, 4. It is also high worldwide after large volcanic eruptions e.g. those of El Chichon (1982.2) and Pinatubo (1991.5). Dust will scatter and absorb light arising above the dust layer (e.g. airglow) or below it (e.g. street-lighting). The altitude of the dust layer is typically a few km, so that the total contributions of airglow and zodiacal light to the brightness of the sky will be diminished (although the scattering will redistribute the light); that of streetlighting may be increased or decreased.

The change in sky brightness due to backscattering of streetlighting depends in a complex way on the size, space density and vertical distributions of the scattering species, on the distribution of streetlamps and on local topography (e.g. obscuring mountains) (Garstang 1989a,b, 1991a,b,c). However, a rough order-of-magnitude upper limit can be placed on the possible brightening of the sky due to this backscattering. We noted above that the intensities of eartbound light from the night sky, and of spacebound light escaping from street lamps, are similar, $\sim$ 10 Wkm^{-2}, so that if a large fraction of the streetlighting is back-scattered, the brightness of the sky could increase by a factor $\sim$ 2, i.e. by $\sim$ 1 mag.

The relationship between extinction A_V and brightening of the sky Δ may be predicted on the basis of an approximate model. About 0.1 mag of the total extinction on La Palma is due to atoms and molecules (King 1985), the rest (A_V - 0.1) to dust. The dust is lower lying and is probably responsible for scattering back most of the street illumination which reaches the observatory. The intensity of the scattered light ($\propto 10^{\Delta/2.5}$ -1) should be proportional to the fraction of starlight extinguished by dust (1-$10^{-(A_V-0.1)/2.5}$). Thus:

$$\Delta = 2.5log10(1 + const(1 - 10^{-(A_V-0.1)/2.5}), \quad (8)$$

where *const* depends on the amount of streetlighting and on the scattering properties of the dust.

Measured sky brightness is plotted against extinction A_V (as recorded for the night by the Carlsberg Automatic Meridian Circle) in Figs. 14, 15. For $A_V < 0.25$ mag, there is no significant variation (< 0.1 mag) of sky brightness with A_V. Approximately 20% of nights on La Palma have $A_V > 0.25$ mag, but our sample includes none satisfying the criteria given in the caption to Fig. 14, and when B, V measurements were made. Measurements *were* made from images taken at low ecliptic and galactic latitude on 21 August 1990 (INT, A_V = 0.44 mag) and 13 June 1996 (JKT, A_V = 0.76 mag), and the sky was markedly bright on both nights (Fig. 15). In part, this brightening is due to the lower ecliptic and galactic latitudes of the observations (Table 2), but the contributions from these effects are much smaller than the observed changes, and in the case of the 1996 data, similar measurements were obtained from the sky background on observations of high-latitude standard stars. On both nights, a similar number of measurements was made in both B and V bands, and the increases in sky brightness $\Delta B, V$ mag in the two bands are similar within the errors, $\Delta B, V \approx 0.3$ mag (after correcting for the variation due to the solar cycle) at extinction 0.44 mag, $\Delta B, V \approx 1.4$ mag at extinction 0.76 mag. Data are available in R band for June 1996, and the brightening is again ≈ 1.4 mag.

The brightening by 0.3 mag when $A_V = 0.44$ mag implies that in equation (8) $const = 1.0$. This then predicts that for $A_V = 0.15$ mag (median non-summer value), $\Delta \approx 0.06$ mag, consistent with the observed value (0.10 mag) given in the last row of Table 4. For A_V = 0.76 mag, on the other hand, the predicted brightening is only $\Delta = 0.5$ mag, compared with an observed 1.4 mag. Clearly the model is naïve for very large extinctions, possibly because the amount of dust *close* to the observatory does not vary in a simple way with the measured extinction of starlight.

The similarity in ΔV and ΔR is consistent with the predictions of Table 4, since the contribution in both bands is determined mainly by the scattering properties of the dust at 5890/6 Å. The similarity ΔB and ΔV is less easily explained, but the ratio is hard to predict, given the possible wavelength-dependence of the fraction scattered, and a probably changing mix of streetlamp types in the light scattered when the extinction is unusually high (the contribution from some towns may be blotted out). More detailed investigation of the effects of dust on sky brightness will be the subject of future work (maybe).

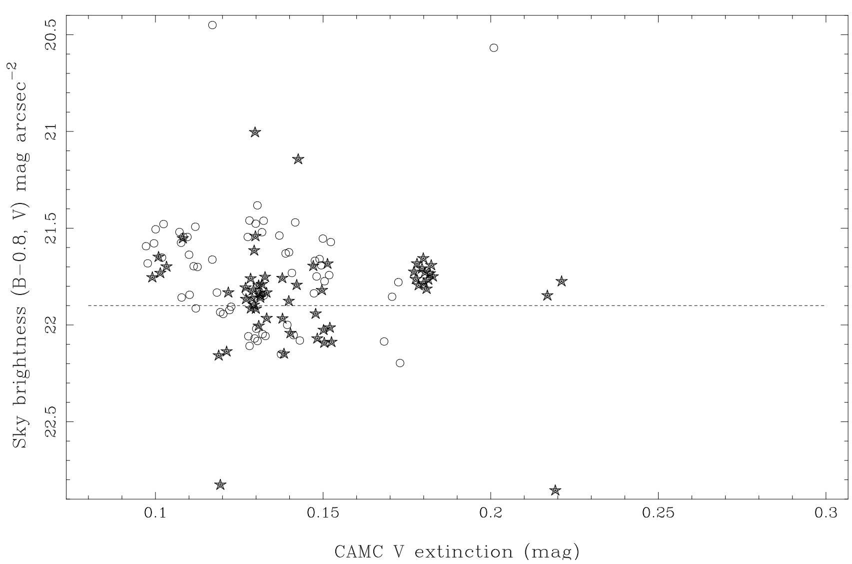

Figure 14: La Palma sky brightness vs mean extinction A_V during the night, as measured by Carlsberg Automatic Meridian Circle. Stars: measurements made after 1994.0, ecliptic latitude $> 30^o$, and satisfying the other criteria given in the caption of Fig. 5, except that relating to extinction. Circles: data satisfying similar criteria but with $\beta > 30^o$.
A correction has been made for the varying contribution of zodiacal light (see caption to Fig. 8).

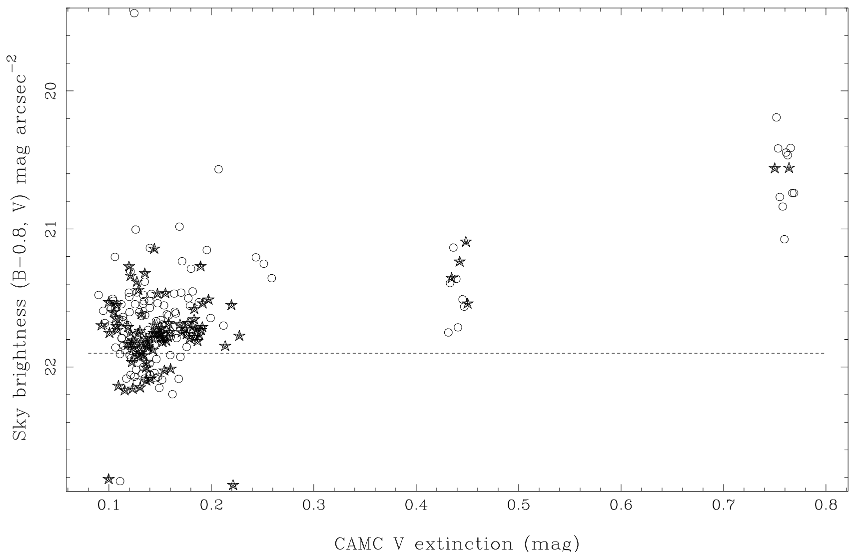

Figure 15: As Fig. 14, but relaxing the selection criteria so that data with lower ecliptic and galactic latitudes from the INT (21 Aug 1990, extinction = 0.44) and JKT (13 June 1996, extinction = 0.76) are included.

3.8 Variation with season, lunar phase and weekday

Dark-of-moon sky brightness does not vary significantly ($<\sim$ 0.1 mag) with season, lunar phase or weekday (possible effects mentioned in Section 1.1). A seasonal effect $<\sim$ 0.1 mag in V, R might be expected from the brightening of the airglow NaD line in winter. Tidal effects might drive a variation with lunar phase. A weekly variation might be driven by the reported weekly variation in the properties of the troposphere (Lenschow 1994, Gordon 1994) or by weekly cycles in use of artificial lighting.

4 Conclusions

The brightness of the moonless night sky above La Palma has been measured from 427 images taken with the Isaac Newton and Jacobus Kapteyn Telescopes during 1987 - 96. The broad-band[3] sky brightness at high ecliptic and galactic latitudes and low airmass, at solar minimum, is given in various units in Table 5.

The sky brightness in V, R is similar to that at other dark sites. In B the sky is measured to be about 0.2 mag brighter than at other sites, but this may be because most of the B data are drawn from 1995 when the B sky brightness was still declining (Krisciunas 1997). The V sky brightness on La Palma (and probably at other sites) is given approximately ($\pm$ 0.1 mag) by the following formula (reflecting the contributions listed in Table 2):

$$V = 27.78 - 2.5 * log_{10}(S_{airglow} + S_{zodiacal} + S_{starlight}) \quad (9)$$

where

$$S_{airglow} = (145 + 130(S_{\odot} - 0.8)/1.2) * airmass \quad (10)$$

$$S_{zodiacal}(\beta < 60^o) = 140 - 90 sin\beta \quad (11)$$

$$S_{zodiacal}(\beta > 60^o) = 60 \quad (12)$$

$$S_{starlight} = 100e^{-|b|/10^o} \quad (13)$$

[3]Because of the significant equivalent widths of the emission lines in the airglow spectrum, the pseudo-continuum sky brightness in V, R seen by spectroscopists is $\approx$ 0.2 mag fainter than the broad-band sky brightness seen by imaging observers

Band	λ/μ	log10 (ν/Hz)	*Jy* mag=0	mag arcsec^{-2}	S_{10}	μJy arcsec^{-2}	γ	R/Å	Wkm^{-2} ster^{-1}
U	0.36	14.92	1810	22.0	205	2.87	0.012	0.64	1.02
B	0.44	14.83	4260	22.7	107	3.54	0.012	0.65	1.03
V	0.55	14.74	3640	21.9	224	6.33	0.017	0.93	1.47
R	0.64	14.67	3080	21.0	515	12.26	0.029	1.55	2.45
I	0.79	14.58	2550	20.0	1294	25.50	0.049	2.61	4.13
J	1.22	14.39	1570	16.6	29648	359.67	0.445	23.80	37.68
H	1.63	14.26	1020	14.4	224905	1772.56	1.640	87.80	138.98
K	2.19	14.14	640	12.0	2051163	10143.32	6.986	373.97	591.92

Table 5: La Palma dark-of-moon sky brightness is given in columns 5 - 10, in various units (see Appendix for details of the conversions). The V sky brightness corresponds to $\approx$ 59 nLamberts. Approximate measurements in J,H, and K, from WHIRCAM on the William Herschel Telescope, are included for convenience. The K value includes an unknown thermal contribution from the telescope; at UKIRT on Mauna Kea the measured K brightness is about 1.5 mag dimmer. Columns 1, 2, 3 and 4 give the band name, wavelength in microns, log10(frequency/Hz) and the equivalent intensity in Jy for apparent mag = 0 (this last from Bessell 1979, Bessell & Brett J.M., 1988). The units of column 8 (γ) are photons s^{-1}m^{-2}Å^{-1}arcsec^{-2}. The last column gives νS_ν in Wkm^{-2}ster^{-1}. The total sky brightnesses in the optical, in microwave-background photons and in cosmic rays, are remarkably similar, a few Wkm^{-2} each. Some of the energy of the cosmic-rays is converted to optical (Cerenkov) photons, but they contribute only $\sim 10^{-4}$ of the total sky brightnes (Jelley 1958).

with a small contribution ($<\sim$ 0.1 mag) from light pollution, much enhanced in the presence of extinction $>$ 0.25 mag. The symbols are as given in Table 2. *airmass* approximates the van Rhijn factor given by equation (2). The colour of the La Palma sky at solar minimum is $B - V \approx 0.8$, $V - R \approx 0.9$.

• The La Palma sky is $\approx$ 0.4 mag brighter on the ecliptic plane than at the ecliptic pole.

• The La Palma sky is $\approx$ 0.4 mag brighter at solar maximum than at solar minimum. Solar activity is close to minimum at the time of writing. The next opportunity to observe the darkest skies from the ground will be $\approx$ 2007 AD.

• The La Palma sky is $\approx$ 0.25 mag brighter at zenith distance 45^o than at the zenith.

• Sky brightness does not change by $>$ 0.1 mag with time after twilight, contrary to the finding of Walker (1988).

• La Palma is a dark site. Continuum-emission light pollution contributes $<$ 0.03 mag to the zenith sky brightness in all bands, well below the 0.1-mag limit recommended by IAU for a dark site. In the NaD line, the contamination is about twice the limit recommended by the IAU, but few spectroscopic observing programmes will be adversely affected. The streetlamp NaD emissions raise the broadband V and R sky brightnesses by $\approx$ 0.08, 0.06 mag respectively. The total contamination is $<$ 0.03 mag in U, $\approx$ 0.02 mag in B, $\approx$ 0.10 mag in V, $\approx$ 0.10 mag in R. The level of contamination is likely to *decrease* in the future.

• The brightness of the sky shows no dependence on extinction A_V, for $A_V < 0.25$ mag (as is the case on 80% of nights). The sample includes two nights with $A_V > 0.25$ mag. With $A_V = 0.4$ mag, the sky was brighter by $\approx$ 0.3 mag, and with $A_V = 0.8$ mag by $\approx$ 1.4 mag, probably because of enhanced scattering of streetlighting by the dust layer.

For sky-limited exposures, an uncertainty of 0.4 mag in the surface brightness of the night sky translates into an uncertainty of a factor of 2 in the exposure time required to reach a given signal-to-noise, with potential wastage of half that time. The measurements reported here of the absolute level of sky brightness, and of the ways in which it varies, allow more efficient use to be made of telescope time.

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Appendix - Light-intensity units

Astronomers, airglow physicists and streetlight manufacturers use a variety of units for measuring light intensity. Some useful conversions are given below.

Physical units of surface brightness:

- μJy arcsec^{-2} $\equiv$ 10^{-32} WHz^{-1}m^{-2}arcsec^{-2}
- WHz^{-1}m^{-2}arcsec^{-2} (F_ν) $\equiv$ 10^{10} λ^2/c WÅ^{-1}m^{-2}arcsec^{-2} (F_λ), i.e. $\nu F_\nu = 10^{10}\lambda F_\lambda$, for ν, λ in Hz and Å
- Rayleigh Å^{-1} $\equiv$ $10^{10}/(4\pi)$ (= 7.96 x 10^8) photons s^{-1} m^{-2} ster^{-1} Å^{-1}
  $\equiv$ 1.24 x 10^7 x (wavelength/m) μJy arcsec^{-2}
- S_{10} $\equiv$ 1 10th-mag star deg^{-2}
- Surface brightness in mag arcsec^{-2} $\equiv$ 27.78 - 2.5log$_{10}$(surface brightness in S_{10} units)
- Surface brightness in mag arcsec^{-2} $\equiv$ 20 - 2.5log$_{10}$ (surface brightness in μJy arcsec^{-2} / K), where K = 18.1, 42.6, 36.4, 30.8, 25.5 μJy arcsec^{-2} for U, B, V, R and I bands respectively (Bessell 1979)
- Surface brightness in Oke's AB mag arcsec^{-2} $\equiv$ -2.5log$_{10}f_\nu$ - 48.60, where f_ν is in erg s^{-1} cm^{-2} Hz^{-1} arcsec^{-2}, i.e. $\equiv$ 23.9 - 2.5 log$_{10}$(μJyarcsec^{-2})
- Surface brightness in mag arcsec^{-2}
  $\approx$ -10 - 2.5log$_{10}$(surface brightness in photons s^{-1}m^{-2}Hz^{-1}arcsec^{-2})

over the range 0.4 - 2.1 μ, to better than 0.03 in the log. This holds because the spectrum of an A0 star approximates $S_\nu \propto \nu$ over the specified wavelength range, so that the intensity in photons s^{-1}m^{-2}Hz^{-1}arcsec^{-2} is independent of frequency.

Units of perceived brightness:

The lumen, used by lighting engineers, is a measure of luminous flux as perceived by the eye. An isotropic source of luminous flux 4π lumens has a luminous intensity of 1 candela = 1 lumen ster^{-1}, and this illuminates a surface 1 m away with illuminance E = 1 lux = 1 lumen m^{-2} = 10^{-4} phot.

Luminance L measures light emitted or reflected by a surface, in lumens ster^{-1} m^{-2} (= cd m^{-2} = nit) (1 stilb = 1 cd cm^{-2}, 1 lambert = $1/\pi$ cd cm^{-2}). Crawford (1997) gives a useful summary of these units and their interconversions.

V = 21.9 mag arcsec^{-2} $\equiv$ 0.00019 cd m^{-2} $\equiv$ 59 nLamberts.

Typical luminance values from Crawford (1997) and Holmes (1997):

Surface	L (cd m^{-2})
Dark night sky	0.0002
Sky at full moon	0.03
Lit road surface at night	0.5
Zenith at sunset	100
Surface of full moon	2500
Candle	10000
Surface of sun	1.6 x 10^9

A surface of luminance L cd m^{-2}, subtending solid angle Ω ster, yields an illuminance $E = L\Omega$ lm m^{-2}, e.g. for the sun, L = 1.6 x 10^9 cd m^{-2}, Ω = 7.7 x 10^{-5} ster, E = 1.2 x 10^5 lum m^{-2}. Note that the values of L, whose units are lm ster^{-1} m^{-2}, can be interpreted in two equivalent ways: as the number of lumens emitted into each steradian by each m^2 of a luminous surface, or as the number of lumens received by each m^2 of a surface from each steradian subtended by an emitter.

At 5550 Å, 1 W $\approx$ 680 lumens (Kaye & Laby 1973). On La Palma, the streetlamps (typically emitting a few thousand lumens each) produce an average of 63 lumens per W of electrical power supplied by the lamp control gear. Approximately half the lumens emitted escape from the lamp housing, and about 10% of the latter are reflected upwards by the ground.